3.—The Stratigraphy of the Moora Group, Western Australia

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This paper is an account of the stratigraphy, petrology, palaeontology and structure of the Moora Group sediments which outcrop along the western margin of the West Australian Shield between Moora and Coorow. The sequence which is believed to be Proterozoic or Lower Palaeozoic in age is formally subdivided into four formations as follows:

(4) Coomberdale Chert (3,303 feet).
(3) Mokadine Formation (330 feet).
(2) Dalaroo Siltstone (500 feet).
(1) Capalcarra Sandstone (160 feet).

The basal Capalcarra Sandstone unconformably overlies a crystalline basement of Archean age. Basement rocks and Moora Group sediments are intruded by quartz dolerite dykes of probable Upper Proterozoic or Lower Palaeozoic age.

The Moora Group is unfossiliferous apart from abundant stromatolites and one problematic organism of unknown affinities.

The major structural feature in the region is the Darling Fault and the Moora Group sediments occupy the shatter zone of this major rift. The sediments have been subject to west-block-down strike faulting along N.N.W. to N. trends and stratigraphic throws up to 1,500 feet have been calculated. The general structure is that of a fractured homocline in which the regional dip of the sediments is 15° W.S.W. to W.

Introduction

The oldest sedimentary sequences of the Perth Basin occur in narrow, north-trending belts of outcrop overlying the Precambrian shield along the eastern margin of the basin. The shield edge is formed by the major Darling-Urella Fault Zone and erosion of the rocks on the eastern wall of this structure has resulted in the preservation of a number of scattered exposures along the flank of the Darling-Urella Scarp from Mundijong in the south to beyond Yandanooka in the north. To date four sedimentary sequences (Fig. 1) have been recognised in this belt, these are: (1) the Cardup Shale, between Mundijong and Kelmscott, (2) the Yandanooka Group, east of Yandanooka and Arrino, (3) the Billeranga Beds, outcropping in the Billeranga Hills and (4) the Moora Group, between Moora and Coorow. This paper is the first detailed study of the Moora Group.

The Moora Group which was formerly considered as a southern extension of the Yandanooka Group (Campbell 1910 and Fairbridge 1950) was studied by the authors in 1955 and the results of this work were first submitted in thesis form as part of the requirements for the degree of Bachelor of Science with Honours in the University of Western Australia. A detailed map of 30 square miles of Moora Group outcrop between Moora and Coomberdale (Plate III) was prepared to illustrate the rock units present and the detailed geological structure of one part of the Moora Group outcrop. A reconnaissance survey of the exposure between Coomberdale and Yandanooka was also made to determine the areal extent and character of the formations defined in the Moora-Coomberdale area.

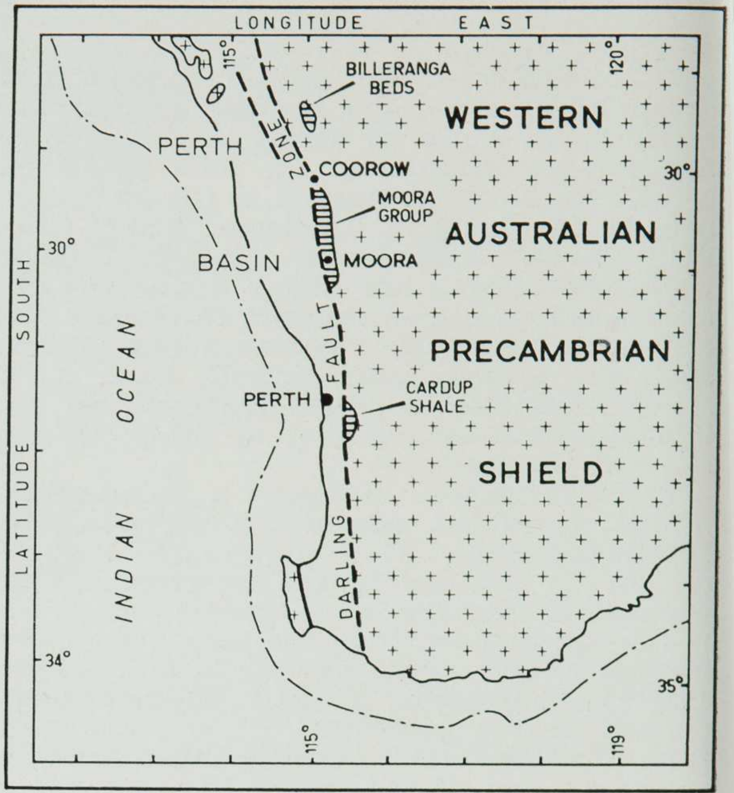

Fig. 1.—Locality map showing distributions of the Moora Group, Billeranga Beds and the Cardup Shale in relation to the larger tectonic features of south-west Western Australia.

The Moora Group is a flat-dipping sequence of arkose, siltstone, orthoquartzite and chert lithologies overlying unconformably, a crystalline basement of Archean age. A stratigraphic subdivision into four formations is proposed herein. The sediment pile is predominantly a stable shelf association of orthoquartzite and silicified limestone (now chert). An initial period of instability and contemporary vulcanism accompanied the deposition of the lower formations of the group. Sedimentary structures and stromatolites indicate a shallow-water origin for the sequence with the palaeogeographic implication of marine transgression of the West Australian Shield from the Perth Basin to the west. The age of the transgression is in doubt; Proterozoic and Lower Palaeozoic ages have been

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suggested by various authorities. Unfortunately the Moora Group is unfossiliferous apart from stromatolites of algal origin and one problematic fossil of doubtful affinities so that no palaeontological age determination is possible. A series of quartz dolerite dykes intrude the Moora Group; Prider (1952) has suggested an Upper Proterozoic "Nullagine" age for the dolerite intrusives of south-west Western Australia and if this is correct the Moora Group can only be Precambrian in age.

Other sedimentary sequences on the shield margin have been studied in some detail. The Cardup Shale is well known due to research from the Department of Geology, University of Western Australia (Prider 1941; Davis 1942; Thomson 1942; and Singh 1958). Woolnough and Somerville (1924) first named the Yandanooka Group (Series) and that sequence has since been examined by Baker (1951), Johnson, de la Hunty and Gleeson (1954) and Playford and Wilmott (in McWhae, Playford, Lindner, Glenister and Balme 1958). At the time of writing the Billeranga Beds are being studied (J. A. Lalor and P. A. Arriens, pers. comm.). Further detailed structural study is needed in the Yandanooka Group and in the northern outcrops of the Moora Group before the early geological history of the Perth Basin can be adequately interpreted.

Previous Work

Previous geological investigations dealing with the sediments at Moora and their northern continuations have been undertaken in connection with artesian water prospects, phosphate deposits in caves and oil prospects in the Perth Basin. Also three regional surveys have been conducted by the W.A. Geological Survey and there have been various brief reconnaissance surveys by the staff and graduate students of the University of Western Australia.

In 1898, Gibb-Maitland described the Moora Group rocks as "a low range of massive quartzites" rising from the flats east of Moora, forming "a portion of the western escarpment of the tableland drained by the head of the Moore River." At this time Gibb-Maitland was unaware of the presence of the Darling Fault and suspected that the Archean rocks and associated "quartzites" continued to the west under a sedimentary onlap. Montgomery (1909) observed impure limestone at the bottom of Jingemia Cave near Watheroo and described surrounding rocks as quartzite and "metamorphic sandstone." Strata at Arrino and Yandanooka, lithologically similar to siltstones at Moora, were described by Campbell (1910) as "quartz conglomerates and submarine tuffs." Campbell noted that ". . . representatives of this series are first met with near Moora, whence they extend as a continuous strip, as yet undefined northward as far as Greenbrook . . . having been noticed and examined at Jingemia, Coorow, Carnamah, Three Springs and Arrino . . .". Blatchford (1912) briefly described the Archean basement to the east as being ". . . usually gneissic in character" and observed that dolerite is intruded into the overlying "quartzites." Saint-Smith (1912) proposed the name "Darling Fault" for the major dislocation which follows the Darling Scarp north along the western margin of the Western Australian Shield.

In 1914 a bore was drilled 2¼ miles west of the railway line at Moora to a depth of 2,200 feet in an endeavour to find an artesian water supply for the town. Jurassic plant fossils were identified in samples from various beds from 665 to 1,200 feet below surface. No fossil material was recognised in samples from the bottom 1,000 feet of the hole (Foreman 1935).

This bore indicated that the fault was somewhere between the sediments east of Moora and the bore-site. Subsequent geophysical work showed that the fault passes very nearly under the townsite of Moora (Thyer and Everingham 1956).

Woodward (1915) suggested that the upper cherty rocks of the Moora sequence originated when carbonate rocks were replaced by silica. More recently, Fairbridge (1950) ascribed the undulose lamination found in chert blocks near Gunyidi (north of Moora on the Geraldton Highway) to algae and identified the genus *Collenia*. At this time the strata east of Moora together with the Yandanooka Group to the north and the Cardup Series (Cardup Shale) to the south were generally considered by local geologists to be late Proterozoic in age because of their supposedly unfossiliferous nature and the presence of dolerite dykes which were considered to have been intruded during late Proterozoic or early Cambrian times (Prider 1948).

A survey of the Perth Basin, including the area of outcrop of the Yandanooka Group and Cardup Shale was carried out by West Australian Petroleum Pty. Ltd. between 1951 and 1957. The results of this survey are detailed in McWhae *et al.* (1958); this paper also contains brief descriptions of the formations of the Moora Group together with their distribution and their probable relation to the Yandanooka Group and Cardup Shale.

Physiography

The Moora Group occurs immediately to the east of the major Darling Fault dislocation which forms the western edge of the West Australian Plateau or Peneplain. The topographic expression of the fault is the Darling Scarp, a prominent meridional feature formed by the uplift of the shield relative to the Perth Basin on the west and by the erosion of the uplifted margin along the fault. South of Moora the scarp is high (1,000 to 1,500 feet above sea level) and fronted by the resistant crystalline rocks of the shield proper; here the plateau rim is dissected by numerous youthful streams. The scarp becomes less prominent from Moora north where the Moora Group sediments form the present scarp face. In this tract the plateau rim reaches altitudes of 800 feet above sea level but the topographic elevation above the alluvial piedmont is only in the order of 200 feet. The Moore River, Kiaka Creek and other streams crossing the scarp in the Moora-Coorow tract are mature with wide alluvial valleys. The dissected terrain grades eastwards into the old landscape of the peneplain proper.

The courses of minor streams in the Moora Group outcrop have been determined by three main factors. First, the homoclinal west dip of the sediments and the variable resistance to erosion of the strata; the result has been the development of north-south valleys between strike ridges of chert and resistant orthoquartzite. Second, the dolerite dykes are highly susceptible to erosion and gullies are developed along the strike of most dykes. Third, streams tend to follow fault zones where crushing and jointing have allowed faster erosion by running water.

Laterite and siliceous duricrust are widespread being sometimes overlain by sand or sandy soil with laterite pebbles. The thickest development of duricrust has taken place above or adjacent to dolerite dykes, but all rock types are susceptible to this type of weathering. The presence of laterite *in situ* on the valley flanks near the scarp suggests that at least some rejuvenation along the Darling Fault occurred before the time of laterite formation.

In general, the groundwaters beneath the chert country are potable, and those underlying the flats to the west of the scarp are brackish (Blatchford 1912).

The Moora Group

The Moora Group outcrops in a narrow, north-trending belt about the 116° E meridian between Moora (latitude 30° 38′ S) and Coorow (latitude 29° 55′ S). The northern continuation of the sediments is obscured by superficial Quaternary sands and the sequence has not been traced further north than Coorow (Fig. 1). The sediments occupy the fragmented terrain on the eastern wall of the Darling Fault shatter zone and unconformably overlie the Archean gneisses and granites of the West Australian Precambrian Shield; they form a homoclinal structure with a regional dip of 15° W.S.W. to W. The older basement complex is exposed to the east of the Moora Group while the western outcrop of the group is limited by a fault-line scarp formed by eastward erosion from the Darling Fault. The Darling Fault is the major structural feature of the region and forms the eastern boundary of the Perth Basin, a taphrogene with some 30,000 feet subsidence (Thyer 1951).

The Moora Group (Fig. 2) consists of four conformable formations of bedded chert, orthoquartzite, arkose and siltstone detailed as follows:

4. *Coomberdale Chert:* Bedded cherts, chert breccias, orthoquartzite, siltstone and rare dolomitic limestones. Thickness 1,890 to 3,300 feet.

3. *Mokadine Formation:* Tuffaceous and calcareous siltstones, arkoses and thin chert beds. Thickness 0 to 330 feet.

2. *Dalaroo Siltstone:* Siltstones, claystones, and arkose with thin chert beds. Thickness 370 to 500 feet.

1. *Capalcarra Sandstone:* Conglomeratic arkoses and orthoquartzites unconformably overlying a crystalline basement complex of granite and gneiss. Thickness 30 to 160 feet.

The Moora Group is extensively block-faulted with west-block-down displacement on a series of north-trending strike faults. Stratigraphic throws of approximately 1,500 feet have been measured. It is considered that the preservation of the sediments on this, the eastern, upthrown block of the major Darling Fault is due to the west-block-down movement in the shatter zone to the east of the master rift.

Moora Group sedimentation was probably brought about and maintained by warping of the shield margin in response to even greater downwarping in the geosyncline area to the west. Available structural evidence indicates that the Moora Group phase preceded the formation of the major Darling Fault dislocation, although Prider (1952) suggests that this was a line of crustal weakness as early as Archean times with west-block-south transcurrent movement. There is little evidence for transcurrent movement in the post-Moora Group faults which are of the gravity type. Pre-Moora Group movements of the Darling Fault may have been dominantly transcurrent.

The Capalcarra Sandstone, the lowermost unit of the group, is characteristically a discontinuous basal sand formed by the winnowing under strand-line conditions of a weathered rock mantle (regolith) derived from the crystalline Archean basement. Instability and seismic activity during deposition of the Capalcarra Sandstone is implied by the sandstone dykes of Capalcarra material which are intruded into the basement granites in the Watheroo area (Logan 1958). The Dalaroo Siltstone and Mokadine Formation contain detrital volcanic material and feldspars as indices of vulcanism and instability within the craton area following the initial transgression. The thick Coomberdale Chert is a stable shelf association of limestone (now chert) and orthoquartzite with abundant evidence of shallow-water origin in ripple marks, mud cracks, cross-bedding, oolites and algal stromatolites. Such a lithofacies aspect is normally developed when slow uniform subsidence of the depositional interface is accompanied by slow clastic and biogenic sedimentation.

The Capalcarra Sandstone

The Capalcarra Sandstone is a sequence of arkosic conglomerate and sandstone lying unconformably on the Archean crystalline basement. The formation has been recognised at Moora and Watheroo. "Capalcarra" is the name of a homestead and property on the north side of the Miling Road, approximately 1½ miles east of Moora. The type section has been taken from an area east of Mokadine Spring near Moora (30° 38′ S; 116° 03′ E). The estimated thicknesses given in the type section below are approximate due to poor outcrop of the formation.

Dalaroo Siltstone

Gray silty claystone.

Capalcarra Sandstone

	Thickness (Feet)
4. Very fine-grained arkose. Not exposed *in situ*. Spec. 36722.*	25

3.	Strongly metasomatised rock whose original texture is not apparent. Affected by adjacent dolerite intrusions, no solid outcrop, rare cobbles in red loamy soil	55
2.	Orthoquartzite. Occurs as rare cobbles in red loamy soil. Coarse-grained, well-sorted, with low porosity, cement microcrystalline quartz. White to gray, orange on weathered surfaces. Rare kaolinised feldspar grains present. Spec. 36720	40
1.	Conglomeratic arkose. Solid outcrop poor, weathered. Medium- to coarse-grained, pink, poorly-sorted, containing angular pebbles of acid crystalline rock, grains of quartz and feldspar. Specs. 36712, 36719, 36716.	40
	Estimated total thickness of Capalcarra Sandstone in type locality, 160 feet.	

Archean Basement

Crystalline complex of granite and acid gneiss.

The Capalcarra Sandstone is 160 feet thick in the type section at Moora and only 30 feet thick at Watheroo. The Watheroo section is complicated by strike faulting and the thickness may well exceed that measured. No other outcrops of the formation were discovered in the reconnaissance survey conducted between Watheroo and Coorow. Orthoquartzites of the Capalcarra Sandstone are intruded into the Archean granite basement at Watheroo to form clastic dykes (Logan 1958). The suggested emplacement mechanism is by slumping of unconsolidated Capalcarra sands into basement fissures and the dykes imply instability during or following deposition of the Capalcarra Sandstone.

Petrography.—The Capalcarra Sandstone is dominantly composed of conglomeratic arkose but minor orthoquartzite and silty sandstone members are developed in the formation.

The conglomeratic arkose is a pink to gray rock composed of poorly sorted, sub-angular to sub-rounded detrital grains of quartz, feldspar and fragments of granitic rocks. There is often a matrix of variable amounts of hematite, sericite, clay and microcrystalline quartz. The orthoquartzite members are usually pink, medium-grained clastics with well-rounded detrital quartz grains and minor amounts of detrital feldspar. The silty sandstones are made up of a poorly sorted admixture of quartz, microcline, plagioclase, muscovite, biotite and composite grains of the same minerals in a matrix of microcrystalline quartz, sericite and iron oxides. Secondary overgrowth of quartz on detrital quartz grains is common throughout the formation.

The Dalaroo Siltstone

The Dalaroo Siltstone is a sequence of claystone, siltstone, arkose, chert and tuff which conformably overlies the Capalcarra Sandstone. At Moora and Coomberdale the formation is overlain by the Mokadine Formation and at Watheroo by the Coomberdale Chert. Basal units of the formation are exposed at Namban. The name is taken from Lake Dalaroo, a large claypan 3 miles west-north-west of Moora. The type section is situated 1½ miles east of Moora townsite, ½ mile east of Mokadine Spring (30° 38′ S; 116° 03′ E). The lower part of the type section shows no exposure *in situ*. An estimate of the sequence of lithofacies and the approximate thickness of units was made by traversing the pebbly outcrop in the direction of dip and taking representative samples. The upper part of the section is more or less affected by lateritisation, and some parts of it are sheared to a low grade of metamorphism.

Specimen No. in Dept. of Geology, University of Western Australia.

The type section of the Dalaroo Siltstone is as follows:

Mokadine Formation

Pale red, massive, cross-bedded, medium-grained arkose. Grains rounded. Conformably overlying the Dalaroo Siltstone.

Dalaroo Siltstone

		Thickness (Feet)
13.	Tuffaceous, sandy siltstone. Outcrops as boulders and flaggy blocks. Has micro current-bedding and ripple markings. In some places is interbedded with beds of very fine-grained arkose, similar to the lowest member of the Mokadine Formation. A lens of massive chert, three feet thick, is present in one part of the locality. The sand-size grains of the siltstone are of feldspar and devitrified volcanic glass. Spec. 36785, 36784	11
12.	Yellow to very dark red, tuffaceous, silty and sandy claystone, outcropping as small cobbles and angular blocks. Exhibits fine graded-bedding in thin section. Subconchoidal fracture present in hand specimens not affected by faulting (those which are affected show fracture-cleavage). Devitrified volcanic glass particles are present in the sand and silt fraction and the unit is possibly in part a waterlain tuff. Spec. 36782, 36783	68
11.	Moderate-red fissile claystone interbedded with fine-grained siltstone (weathers yellow). Almost symmetrical ripple marks on one hand-specimen measured 2 cm between crests and were 2 mm in amplitude. Silty laminae contain quartz, saussuritised feldspar, biotite, muscovite, and iron-ore all in a siliceous cement. Spec. 36780, 36781	35
10.	Yellow, gray and purple fissile claystone, interbedded with moderate -red, fine-grained fissile siltstone. Angular grains of quartz and feldspar, flakes of muscovite and biotite are main silt-sized components. Spec. 36780	20
9.	Fine-grained, purple to gray fissile siltstone. Small-scale slumping evident. Main minerals of the silt grade are feldspar, iron-ore and muscovite. Spec. 36729	10
8.	White chert. Stands out as a subsidiary ridge on the eastern slope of Mokadine Hill. Banded in parts. On weathered surfaces it is drusy and saccharoidal	6
7.	Claystone. The outcrop has been bleached during the lateritisation process. Occasional quartz grains are all that show up in thin section. The hand specimen exhibits a pink banding	48
6.	Gray-pink, medium to coarse-grained arkose. No outcrop *in situ*. In thin section, sub-rounded potash feldspar constitutes 50 per cent. of the rock. Larger rounded quartz grains surrounded by authigenic quartz outgrowths and fine angular grains of iron-ore, complete the assemblage. Spec. 36727	51
5.	Massive gray-red silty claystone and quartzose granule conglomerate. The siltstone has good parting along bedding planes, and its silt-sized components are feldspar, muscovite	

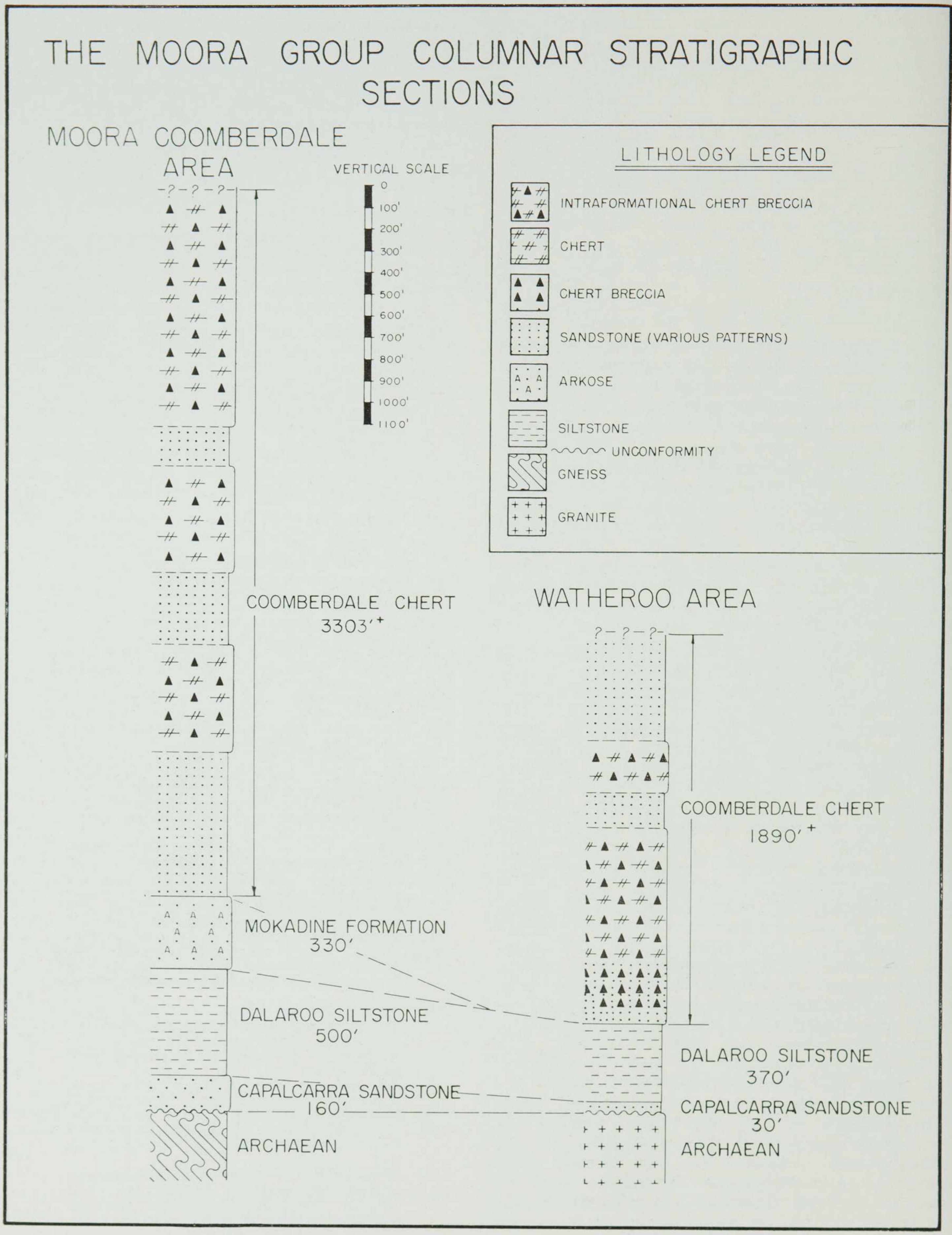


Fig. 2.—Columnar stratigraphic sections of the Moora Group at the type area (Moora-Coomberdale) and Watheroo.

and angular grains of iron-ore. The matrix of the granule conglomerate is too weathered for determination of its original content. The quartz granules are sub-rounded. The relationship of the two rock types in the unit is not discernible because of lack of solid outcrop, but the presence of the granule conglomerate may indicate that strata similar to the overlying arkose are present in this member. Spec. 36726 68

4. Gray-red silty sandstone. No outcrop *in situ*. Friable cobbles in clayey loam. Contains dark red mudballs 1.5 mm in diameter and coarse grains of kaolinised feldspar and muscovite flakes. Spec. 36725 25
3. Gray-red silty shale, weathering yellow and orange. No outcrop *in situ*. Individual laminae have constant thickness. Constituent minerals are clays and quartz 75
2. Moderate-red to light brown fine-grained arkose. No outcrop *in situ*. Surface debris largely kaolinised. A cement of authigenic quartz is present, also secondary chlorite and sericite. Spec. 36724 34
1. Silty claystone. No outcrop *in situ*. In the area examined where debris from this unit is exposed, intrusion of dolerite dykes nearby has resulted in the formation of sericite and chlorite in the rock and the silicification of the joint planes. Silt-sized particles of quartz and feldspar are corroded. Spec. 36723 54

Estimated total thickness of the Dalaroo Siltstone, 500 feet.

Capalcarra Sandstone

Very fine-grained arkose. Spec. 36722.

The thickness of the Dalaroo Siltstone ranges from 500 feet at Moora to 370 feet at Watheroo. The possibility of strike-faulting at Watheroo makes the value given here indefinite. At Coomberdale the basal units of the formation crop out to the east of the Noondine Fault, the section being 80 feet thick while the upper members outcrop west of the fault with a thickness of 360 feet.

The dominant rock types are siltstone and claystone containing quartz, feldspar and clay minerals. The Moora section contains 80% claystone and siltstone; the Coomberdale section 100% and the Watheroo section is composed of about 70% of these lithologies. Some units contain tuffaceous and detrital carbonate material. At the Coomberdale locality one unit which is certainly pyroclastic occurs in the upper part of the section immediately below the contact with the overlying Mokadine Formation. Undoubted tuffaceous siltstones also occur in the upper unit of the Dalaroo Siltstone at Watheroo. At this locality the upper units of the Dalaroo Siltstone crop out as resistant strike ridges trending 150°. The highest unit is a sequence of tuffaceous siltstone with lesser quantities of interbedded arenite and conglomerate. Cross-bedding, ripple marks (Fig. 3) and graded and lensing strata are common. Fragments of volcanic rock occur throughout and are associated with detrital carbonate in a number of beds. Rare conglomerate beds up to 30 cm thick contain pebbles of quartz, andesite, quartzite and granite. Other units of the Watheroo section are not well preserved in outcrop. They consist chiefly of red-brown shales with subordinate silicified limestones and arkose intercalations.

Petrography.—The siltstones of the formation can be divided into three end-member types on a basis of mineralogical content. These are: (1) arkosic siltstone, (2) calcareous siltstone and (3) tuffaceous siltstone. However these subdivisions are not distinct and there is considerable intergradation between end members.

Arkosic siltstones: The siltstones of the arkosic suite of sedimentary rocks have quartz, feldspar and mica as the principal silt-size detrital constituents. The rock type is usually brown or brown-red in colour, except adjacent to dolerite intrusions where the development of secondary chlorite imparts a gray-green colour to the rock. The structure varies from massive to fissile; the parting along bedding planes from good to poor. Jointing is generally smooth and regular. The arkosic siltstones contain small-scale sedimentary structures such as ripple marks (1.5 mm wavelength), graded-bedding, cross-bedding (5 cm thick), mud-ball conglomerates (1.5 mm in diameter) and small slump structures. In thin section siltsize detrital grains of feldspar, muscovite and biotite are observed in a matrix of the same minerals as well as sericite, chlorite, hematite, magnetite and clay minerals. A siliceous cement is commonly developed. Weathering processes, particularly lateritisation, effect colour changes due to concentration, alteration or removal of iron oxides and the kaolinisation of the feldspars.

Fig. 3.—Ripple-marked slab of tuffaceous and calcareous siltstone from unit 11 of the Dalaroo Siltstone at Watheroo, Western Australia.

Calcareous siltstone: Siltstones containing detrital carbonate occur in the topmost unit of the Watheroo section and in the basal units of the Coomberdale section. The occurrence of clastic carbonate with pyroclastics at Watheroo has been described above. Beds and lenses of pink, rounded carbonate particles (up to 2 mm) occur in a shaley deep-red siltstone matrix. As seen in thin section the detrital carbonate is intermixed with detrital quartz, feldspar and microcrystalline volcanic rock fragments; the matrix is dense and composed of sericite, chlorite and iron-stained material. Partial replacement of the carbonate by chlorite is indicated in some sections. The calcareous unit at Coomberdale is red-purple, massive with widely-spaced joint planes and uneven fracture. The carbonate occurs as rhomb-shaped grains with microcline and quartz in a matrix of fine silt and iron-stained clay. Weathered surfaces of the calcareous siltstones resemble vesicular basalt due to solution of the carbonate grains which leave cavities in the matrix.

Tuffaceous siltstone: The tuffaceous siltstones in the formation typically contain detrital fragments of vesicular volcanic glass and/or microcrystalline igneous rocks of andesitic composition and detrital feldspars. Detrital quartz is not abundant. The matrix is composed of finely disseminated hematite with sericite and chlorite. Diagenesis has resulted in devitrification of glassy matter, potash enrichment of feldspars and development of secondary chlorite and epidote. The pyroclastic tuff at Coomberdale is interbedded with epiclastic tuffaceous siltstones. It is a gray, massive rock, poorly bedded containing angular blocks of red-purple siltstone. Volcanic glass fragments which constitute approximately 60% of the rock are often bent or warped around each other denoting a plastic state at deposition. The glass shards contain small inclusions of iron-ore, feldspar and quartz as well as clay aggregates. Small xenoblasts of epidote occur throughout the rock.

A number of arkosic sandstone units or members are developed in the Dalaroo Siltstone. Arkosic sandstones occurring low in the sequence resemble similar rocks in the Capalcarra Sandstone while those developed higher in the sequence are similar to the arkoses of the overlying Mokadine Formation. Microcline is the dominant feldspar.

A thin chert unit occurs interbedded in the type section of the Dalaroo Siltstone. The chert is highly weathered with a saccharoidal appearance and a faint stromatolitic banding. The Watheroo section also contains a few chert units. There is evidence here for a replacement origin for the chert as there are remnants of calcarenite and laminated algal limestone breccias.

The Mokadine Formation

The Mokadine Formation is a sequence of siltstone and claystone, well-sorted arkose and feldspathic sandstone and minor chert which conformably overlies the Dalaroo Siltstone and is overlain by the Coomberdale Chert. The name is taken from Mokadine Spring, a small soak 1½ miles east-north-east of Moora (the highland surrounding the spring where the type section of the formation is exposed is known locally as Mokadine Hill). The formation was originally named "Mokadine Arkose" (McWhae *et al.* 1958) because of the prominence of arkose units in the field and the prevalence through the formation of clastic sediments containing microcline and quartz. However, true arkose units make up only a small part of the total thickness in the type section. Therefore, to comply with the Australian Code of Stratigraphic Nomenclature of 1956, the name is amended to Mokadine Formation.

The type section near Mokadine Spring (30° 38′ S; 116° 02′ E) is as follows:

Noondine Member, Coomberdale Chert

Orthoquartzite and silicified limestone containing the Coomberdale problematic fossils. Conformably overlies the Mokadine Formation.

Mokadine Formation

		Thickness (Feet)
11.	Gray and grayish-purple siltstone. Crops out as blocks and cobbles in soil. Flaggy to shaly, with alternate purple and gray indistinctly separated laminae. Dense, non-friable with smooth break along joints and bedding planes. Gray laminae are 50% microcrystalline quartz cement and 46% detrital microcline and quartz with iron-ore and epidote as minor constituents. Purple laminae, in addition to the above constituents, contain abundant microcrystalline grains of hematite. Spec. 36818	10-20
10.	Grayish red massive silty claystone. Weathered joint blocks litter uncleared area. Contains mud balls. Silt-sized components are kaolinised feldspar and rare shreds of sericite and chlorite in a matrix of iron-stained clay. Spec. 36817	55 (with underlying member)
9.	Pale red-purple conglomeratic feldspathic sandstone, white and orange on exposed surfaces. The pebbles in the conglomerate are chert. The remainder is made up of rounded quartz grains with sericite inclusions (49%), kaolinised feldspar grains (9%), rounded detrital chert grains and rare muscovite flakes (1%) and a microcrystalline quartz cement with carbonate inclusions (37%). Spec. 36816.	
8.	Banded chert, white to gray. Exposure of angular joint blocks	10
7.	Grayish-red shaly calcareous siltstone. In thin section it is made up of laminae about 5 mm thick, each grading from coarse siltstone at the base to thin sub-laminae of fine siltstone at the top. The detrital constituents are carbonate (up to 25%), plagioclase, potash feldspar, muscovite and quartz in varying proportions in a matrix (50-90%) of iron-stained clay, sericite and chlorite	105
6.	Arkose, exposed *in situ*. Progressively lighter in colour from bottom to top, grayish-red to light brown. Shaly at the base, massive at the top. The roundness of quartz grains increases upwards. Detrital constituents are sub-angular to rounded quartz (50-60%), surrounded by authigenic overgrowths, well-rounded feldspar, chiefly microcline (35-50%) and muscovite and magnetite (3-5%). The cement (10-15%) is siliceous and contains hematite inclusions. Spec. 36813, 36814	50

5.	Tuffaceous siltstone exposed *in situ*. Grayish-red to blackish-red. Made up of laminae of claystone and siltstone with occasional layers of sandy siltstone. Fracture, semiconchoidal; hardness, even. Silt and sand-sized grains of feldspar and devitrified glass in varying proportions lie in an iron-stained clay matrix. Grains of optically positive plagioclase form stout lath-shaped euhedra sometimes rimmed with devitrified glass. Grains composed wholly of the latter are also present. The devitrified glass is rich in potash feldspar, anhedra of chlorite and crystals of magnetite. The latter mineral also occurs as rounded grains. Quartz replaces parts of some plagioclase laths. Spec. 36812	28
4.	Feldspathic sandstone, exposed *in situ*. Dark orange-yellow to light gray. Flaggy to massive. Silicified, hard and non-friable. Medium-grained, well-sorted. Constituents are well-rounded heavily overgrown quartz (85%), rounded saussuritised microcline (13%) and iron-ore and chert grains (2%)	36
3.	Arkose, cropping out as angular boulders. Fine-grained with medium-grained layers. Light brown, flaggy and friable. Constituents are well-rounded grains of quartz, with sutured overgrowths on the grains and well-rounded grains of microcrystalline chert (50%), saussuritised and kaolinised feldspar, chiefly microcline, with rare andesine (35-50%), iron-ore, rare colourless non-pleochroic zircons and very rare purple tourmaline (1%), and the remainder siliceous cement. Spec. 36810	13
2.	Fine-grained arkose, exposed *in situ*. Grayish red-purple. Shaly, with alternating finer and coarser laminae up to 5 mm thick. Non-friable. In thin section, grains show an average roundness of 0.2 with a correspondingly low sphericity. Quartz (39%) is overgrown with siliceous cement (11%) which contains abundant red highly refringent inclusions of hematite. Feldspar (26%) mainly microcline with some oligoclase. Iron oxide is present as detrital magnetite and secondary hematite. Spec. 36809	11
1.	Medium-grained arkose, cropping out as a low cliff with talus at the base. Cross-bedded. Non-friable, weathers to a light brown, but when fresh, pale red. Grains well-rounded, 64% quartz, with undulose extinction and authigenic overgrowths, 28% microcline. Small amount of detrital chert, iron-ore and colourless zircon. Cement is microcrystalline quartz. Spec. 36808	16
	Total thickness of Mokadine Formation 330 feet.	

Dalaroo Siltstone

Tuffaceous sandy siltstone. Spec. 36784, 36785.

The Mokadine Formation outcrops in the Moora-Coomberdale area but it is absent from the Moora Group section at Watheroo where the Coomberdale Chert immediately overlies the Dalaroo Siltstone with apparent conformity. The maximum measured thickness is the 330 feet of the type section at Mokadine Hill, Moora. The formation outcrops again at Coomberdale where a monotonous succession, 300 feet thick, of arkose and feldspathic sandstone occurs overlying tuffaceous upper units of the Dalaroo Siltstone. The Mokadine Formation has not been recognised north of Coomberdale but since the outcrop between Coomberdale and Watheroo was not mapped in detail there is a possibility that exposures may exist in this area.

Petrography.—The Mokadine Formation is composed of two dominant lithological suites, arkose and feldspathic sandstone and arkosic siltstone. There are also minor intercalations of silicified limestone (now chert).

Arkose and feldspathic sandstones comprise 60% of the type section at Moora and almost 100% of the Coomberdale exposures of the formation. The feldspathic sandstone suite are orange to pink, well-sorted arenites with 10 to 25% microcline feldspar, approximately 70% detrital quartz, 5% microcrystalline or sutured quartz aggregates and magnetite (up to 5%). The individual grains are sub-rounded to rounded and feldspar is usually more highly rounded than quartz. Detrital quartz grains commonly have authigenic quartz overgrowth. The cement is siliceous. Secondary sericite and epidote are occasionally developed.

Arkosic siltsones and rare tuffaceous siltstones comprise 34% of the type section at Mokadine Hill and also outcrop in the Moora area to the north of the Moore River. The arkosic siltstones are grayish red to brownish red rocks composed chiefly of silt-size detrital feldspar with lesser amounts of detrital quartz, detrital carbonate and in some members volcanic glass. The matrix consists chiefly of iron-stained clay, sericite and chlorite.

The Coomberdale Chert

The name Coomberdale Chert is applied to the sequence of bedded cherts, chert breccias, orthoquartzites and silicified limestones overlying the Mokadine Formation in the type section at Coomberdale and the Dalaroo Siltstone at Watheroo. The upper boundary of the Coomberdale Chert has not been observed. The formation is named after Coomberdale, a small railway siding on the Perth to Geraldton line, 130 miles north of Perth. The type section which is exposed in a series of fault blocks in the area south of Coomberdale (latitude 30° 28′ S; longitude 116° 02′ E) is detailed as follows:

Erosion Surface
Coomberdale Chert

		Thickness (Feet)
22.	Chert, intraformational slump breccias and folds are common features. Stromatolite structures are present; exposure varies from cliff to bouldery outcrop	1,100 +
21.	Koolera quartz sandstone member; fine to medium-grained orthoquartzites with secondary overgrowth on the detrital quartz to complete cementation. Chert breccias and conglomerates ranging from cobble to granule size are prominent especially at the base. Rare beds of massive, brown siltstone are present. Sedimentary structures are current ripple marks, mud cracks, intraformational mud curls and clay galls. Outcrop is bouldery	160
20.	Chert, intraformational slump breccias and stromatolites. The strongly jointed chert varies from cliff to bouldery outcrop	480
19.	Kiaka quartz sandstone member, fine to medium-grained orthoquartzites with chert breccias at the base and with lenses of bedded chert which are partly stromatolitic. The orthoquartzites are red, brown and white in colour and commonly massively bedded. Current ripples are common	380

18.	Chert as for unit 21	550+
17.	Orthoquartzite with 40% chert cement, white, fine-grained. The unit is dominantly composed of silicified tubes of a problematic fossil which may be an alga, stromatoporoid or coral Rare small algal colonies of *Collenia columnaris* Fenton and Fenton are present	65
16.	Orthoquartzite, medium-grained with a chert cement, cross-bedded	80
15.	Orthoquartzite, white, medium to coarse-grained, massively bedded	71
14.	Orthoquartzite, mottled brown and white, strongly current-bedded. Chert cement 1 to 5%. Sorting poor, approximate average grain size 0.6 mm	10
13.	No outcrop unit, obscured by sand cover	10
12.	Chert, white opaque massive	15
11.	Orthoquartzite, white, medium-grained, massively bedded, chert cement	35
10.	Chert, white, thinly bedded with detrital quartz grains in thin laminae. Detrital grains 0.1 mm diameter. A palimpsest oolitic texture is visible in the chert	40
9.	Orthoquartzite, pink fine to medium-grained, with well-developed current-bedding. A chert cement is present (40%). Rare chert fragments are also visible in thin section	86
8.	Orthoquartzite, light gray, fine-grained, cross-bedded, clay cement	1
7.	Orthoquartzite, pink, fine to medium-grained with well-developed current-bedding, roundness of grains low, size sorting poor. The cement is a clay of micaceous habit	5
6.	Orthoquartzite, white, medium-grained, well-sorted, 6″ x 12″ lenses of pink orthoquartzite are present. Silicified problematica colonies occur at the base. Chert occurs as a cement and in thin beds (10 to 40 mm) and irregular lenses throughout the unit	30
5.	Unit obscured by sand cover	87
4.	Orthoquartzite, white, coarse-grained, well-sorted, approximate average grain size 1 to 1.5 mm, massively bedded	3
3.	Orthoquartzite, white, medium-grained, massively bedded with silicified problematica colonies in a biostromal development. Five cm beds of white and pink chert are also present	40
2.	Orthoquartzite, white, medium-grained, well-sorted, massively bedded	20
1.	Orthoquartzite red to white, fine to medium-grained, strongly current-bedded. Rare current ripples of 40 mm wave length and 17 mm amplitude are present. Thin section discloses a chert cement and silicified oolites	35
	Total thickness of Coomberdale Chert	3,303

Mokadine Formation

The Coomberdale Chert outcrops in a two-mile wide belt between Moora and Coorow. The western outcrop boundary forms the front of the Darling Scarp. In the Moora-Coomberdale area the formation overlies the Mokadine Formation with apparent conformity. At Watheroo this arkose is not represented in the section and the Coomberdale Chert rests directly on the Dalaroo Siltstone.

The Watheroo section of the formation is characterised by thick members composed of clastic breccias. North of Watheroo outcrops are mainly obscured by sand plain cover; at Gunyidi scattered solid outcrop of chert and intraformational (slump) breccias project above the sand cover. Fairbridge (1950) recorded *Collenia* from the Coomberdale Chert in this area. In the vicinity of Coorow a few scattered outcrops of chert are found in the sand plain and at Coorow Cave, 5½ miles south-west of Coorow townsite, a silicified dolomitic limestone containing stromatolites is exposed in the walls of the cave. The limestone is overlain by sandstones bearing ripple marks and cross-bedding. A two directional system of vertical joints filled with quartz stand out on the weathered surface as box work structures.

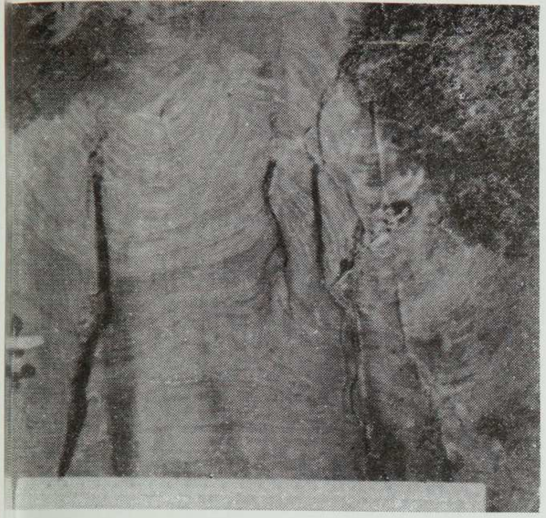
Like other formations in the Moora Group the Coomberdale Chert was not traced in outcrop north of Coorow. J. A. Lalor and P. A. Arriens of the Department of Geology, University of Western Australia, report lithologically similar cherts in the Billeranga Hills area which may be part of a northerly extension of the formation but at the time of writing no continuity has been traced between Coorow and the Billeranga Hills.

Chert

Chert forms a series of thick strongly jointed members in the formation. They are strongly banded rocks with light gray, dark gray and pink laminae; much of the lamination has a micro-undulation of a few cms amplitude which is stromatolitic in nature. The chert is a novaculite type composed predominantly of microcrystalline quartz with a mosaic texture of interlocking polyhedral quartz crystals, 0.01 to 0.02 mm crystal size. According to Folk and Weaver (1952) such a texture results from crystallisation about closely spaced centres distributed in a three-dimensional plan. Chalcedonic quartz is very rare and only occurs in spherulites and bands around "agate" or colloform textures.

Minute, equidimensional carbonate inclusions, probably calcite are almost universally distributed throughout the chert members. The inclusions are relicts of the original carbonate sediments which have been silica metasomatised to form chert. The criteria for such a replacement are outlined and briefly discussed elsewhere in this paper. Dolomite rhombs occur in many of the chert beds and sometimes these are replaced by quartz to form dolocasts—rhombic quartz crystals pseudomorphous after dolomite.

Intraformational folding and brecciation.—Symmetrical and asymmetrical folds, minor overfolds and miniature nappes are beautifully exposed in cliff sections of the bedded cherts. This contortion is strictly intraformational and the folds grade upwards or downwards into zones of intraformational chert breccia. The amplitude of the contortion varies from one to several feet, but the impression is that these are merely smaller folds on the flanks of larger intraformational undulations. The smaller synclines are broadly convex, the anticlines more often sharply constricted at the crest (Plate I, Fig. 1) suggesting folding or slumping under minimal load. Intraformational overfolding and subsequent breakage of the overfold has produced miniature nappes which have been thrust forward over flat-lying undisturbed beds; nappe formation is uncommon due most likely to the general competency of some laminae which fail by fracture to produce breccias. One



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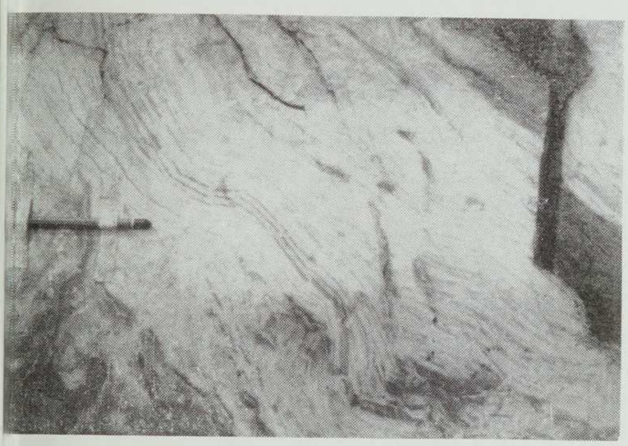

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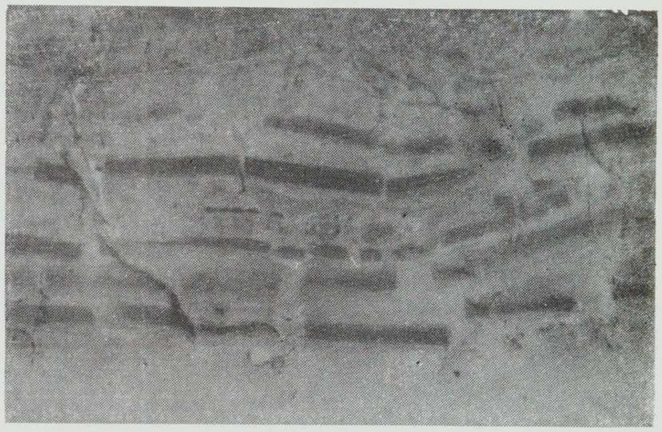

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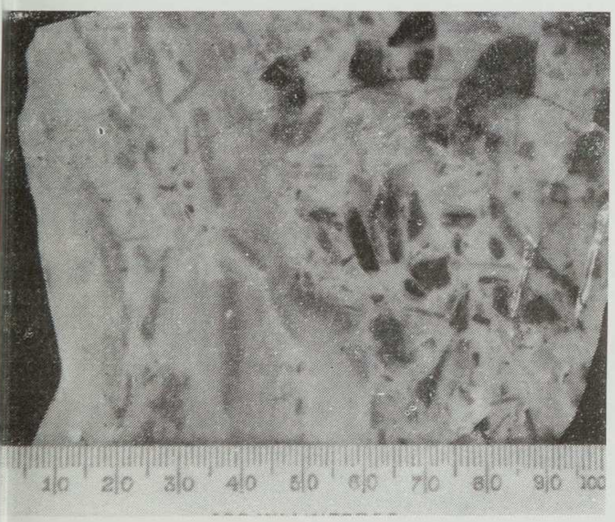

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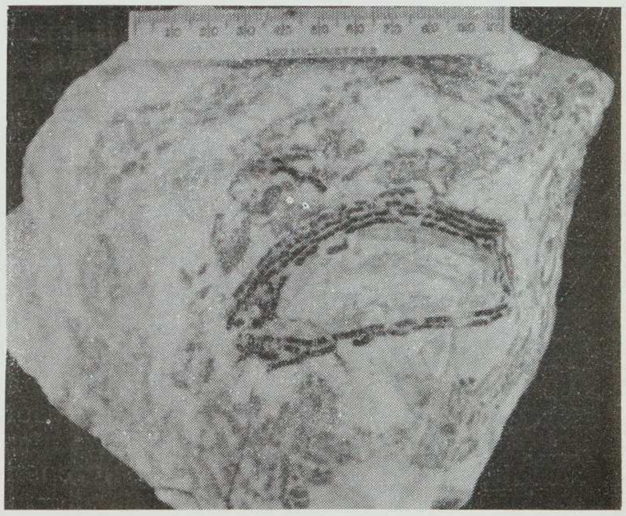

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PLATE I

Fig. 1.—Intraformational slump folding exposed on a vertical joint face in the Coomberdale Chert at Kiaka Cliff, Coomberdale. Broadly convex syncline and sharply folded anticline grade down into almost undisturbed laminae. Scale is a one foot rule.

Fig. 2.—Intraformational contortion with incipient brecciation of thin, dark gray laminae in chert at Kiaka Cliff, Coomberdale.

Fig. 3.—Intraformational chert breccia and folding in the Coomberdale Chert at Kiaka Cliff, Coomberdale. The breccia fragments are not disturbed from the original bedding positions.

Fig. 4.—Intraformational chert breccia in which the fragments are little disturbed from the original bedding directions. The fragments are approximately 20 to 30 mm in length.

Fig. 5.—Intraformational chert breccia from the Coomberdale Chert at Kiaka Cliff, Coomberdale. No trace of original bedding is preserved in this specimen. Compare with Figures 3 and 4 above.

Fig. 6.—Cross-section of a "snowball' or spiral slump in chert from the Coomberdale Chert, Coomberdale. The spirally arranged laminae have been brecciated and flattened on the under surface, presumably where the slump came to rest.

"snowball" or spiral slump (Plate I, Fig. 6) was observed in the chert outcrop at Kiaka Cliff. The spiral slump has a diameter of 250 mm and is composed of spirally arranged brecciated laminae flattened on one side; the side on which the snowball came to rest. Fairbridge (1942) discusses snowball or spiral slumps as features due to rotary movement of sediment down slopes and the gathering of sediment into the rolling mass.

Continuity of the chert bedding can be traced laterally for only short distances before the bedding is disrupted and passes into zones of intraformational chert breccia. The bedding may be totally or partially disrupted (Plate I, Figs. 2, 3, 5). The breccia fragments are light gray to dark gray in colour and angularly tabular in shape. Their elongation is parallel to the original bedding (Plate I, Figs. 3, 4) and their length ranges from 3 mm to 100 mm with an average length around 25 mm; the thickness of the fragments is dependent on the thickness of the original bedding or laminae from which the fragments were derived, averaging about 10 mm. The cement or matrix is a white chert.

Brecciation is clearly due to the intraformational stresses which caused the contortion and all gradations exist between partially brecciated beds in which the laminae are contorted and broken but undisturbed from their bedding positions (Plate I, Figs. 2, 3, 4) and chert breccias in which no trace of the original bedding is preserved (Plate I, Fig. 5). The final phase in the intraformational breakup is the plastic injection of intraformational breccia as sills and dykes into adjacent beds. These structures are similar to clastic dykes in sedimentary strata which according to Fairbridge (1942) are features of regions with penecontemporaneous slumping.

While intensity of movement must be the chief factor in determining the nature and extent of folding and brecciation within the formation, the lithology (or more correctly the physical state) can be shown to have a marked influence. Hence intense contortion and intraformational brecciation occurs in the members where thick, white laminae (20 to 30 mm) predominate over thin (5 mm) gray laminae. At other localities where the gray laminae are dominant in the section, the bedding is only slightly disturbed or thrown into folds without brecciation. It is deduced that beds and laminae now represented by white chert behaved in a plastic manner and failed by flowage under stress. On the other hand the laminae now represented by gray chert reacted competently and failed by fracturing to form the breccia fragments.

Gravity sliding is a likely mechanism for this form of intraformational disturbance and two conditions are prerequisite: one, an unconsolidated state of the sliding mass and two, an inclination of the substratum on which the sediments can slide. Brecciation requires the presence of lithified laminae interbedded in the moving sediment mass. The relationship of folding to brecciation indicates that the pre-fold sediments were a complex of lithified but fragile beds and laminae alternating with unlithified incompetent beds. With this condition and under stresses set up in the sliding sediment mass, beds of incompetent nature flowed and contorted readily while interbedded competent beds fractured into breccia fragments.

Lees (1928) ascribed intraformational folding and brecciation in the Campanian cherts of Palestine, Syria and Jordan to internal forces of expansion of precipitated silica gel which shattered the interbedded limestone (and apparently chert) into fragments. However Fairbridge (1942) considered this intraformational folding was due to penecontemporaneous subaqueous slumping and related the brecciation to the same process. The questions of intraformational slumping and chert origin have been linked since the presence of slump features has led to the assumption of a colloidal silica gel state for the original rock and hence a distinct prejudice against a metasomatic origin for the cherts containing them, Lees (1928), Fairbridge (1942) and James (1954). That cherts are necessarily syngenetic if they contain slump features is not a completely sound argument for slumping implies only a certain set of physical conditions which may be unrelated to chemical composition.

Origin of Chert

The controversial topic of chert origin, whether syngenetic or epigenetic, has been debated in the geological literature for many years. It is not our intention to discuss the matter in this paper as we feel it has been adequately covered by numerous authors. The Coomberdale Chert is considered by the writers to be due to the silica metasomatism of an original carbonate rock formation; a post-consolidation replacement which has preserved most of the original sedimentary structures and textures of the metasome. This conclusion has been reached after careful evaluation of all the criteria for chert origin present in the field and in thin section. The criteria observed in the Coomberdale Chert are overwhelmingly in favour of replacement origin of chert. These observations are listed, discussed and evaluated below:

(a) Gradation of chert rock types into similar carbonate rock types in outcrop.—The strongest argument for replacement origin can be seen in the walls of Jingemia cave, Watheroo, where there is a gradation from chert breccias (with orthoquartzite matrix and microcrystalline quartz cement) into dolomitic limestone breccias (with orthoquartzite matrix and carbonate cement). In this locality chert breccias on the surface grade down into the carbonate rocks with similar textures and structures at depths of 30 to 40 feet. Selective replacement is indicated in thin sections from this exposure for the coarse, crystalline calcite of the cement is replaced in the earliest stages of metasomatism while the dense cryptocrystalline carbonate of the fragments is unaffected. With progressive increase in SiO_2 the fragments are replaced by microcrystalline quartz which even in the final stages of chertification is replete with minute relict inclusions of carbonate.

(b) Silicification of carbonate fossils.—Chertified stromatolites are abundant in the bedded cherts and also occur as fragments in the clastic chert breccias of the Watheroo section. This evidence speaks for itself.

(c) Silicification of oolites.—Silicified oolites and oolitic textures present in the Noondine member point to a replacement process where the original carbonate oolites have been replaced by silica. This criterion for replacement was first advanced by Van Tuyl (1918) and most workers agree that it is valid. One exception has been a paper by Krynine *et al.* (1941) which describes primary siliceous oolites interbedded with carbonate oolites in the Upper Cambrian of central Pennsylvania;

however, Choquette (1955) refutes the hypothesis of Krynine *et al.* (1941) and believes that this oolite also owes its character to the silicification of an original carbonate oolite.

(d) Relict carbonate inclusions in chert.—Minute, relict inclusions of carbonate, probably calcite, are almost universally distributed in the chert of the formation; they are particularly abundant in laminae in which the microcrystalline quartz is approximately 0.2 mm diameter and apparently physico-chemical conditions in these laminae were more suitable for the preservation of the inclusions after silicification. There is little doubt that these inclusions are relict as their formation has been observed along the carbonate-microcrystalline quartz interface in partially replaced dolomitic limestones. Dolomite rhombs which occur occasionally in the chert are also to be regarded as relict after replacement; in some instances the dolomite rhombs themselves may be replaced by quartz with the formation of quartz dolocasts after dolomite. Perhaps the best criterion for selective replacement is seen in the dolomitic limestones in which the rhombs are zoned and contain calcite cores. In many instances the calcite has been selectively replaced, resulting in rhombs with a core of microcrystalline quartz rimmed with dolomite.

(e) Widespread quartz overgrowth in the clastic members of the formation.—Most of the orthoquartzites in the Coomberdale Chert have secondary enlargement of quartz in optical continuity with the detrital quartz grains. Widespread quartz overgrowth is not direct evidence for a replacement origin of the chert; what is indicated is that large amounts of silica circulated throughout the sequence. Chert cements and chert fragments in the orthoquartzite members can reasonably be regarded as products of SiO_2 metasomatism of original carbonate cements and fragments, particularly in view of the occurrence of silicified fossil fragments and silicified oolites in the detrital fraction. This argument is further strengthened by the findings of Folk and Weaver (1952) who point out that silica deposited in intergranular spaces would be in the form of chalcedony whereas microcrystalline quartz is commonly formed by replacement of carbonate.

The present writers consider that the chert fragments and microcrystalline cements in many of the orthoquartzites of the formation were produced by silica solutions replacing the original carbonate fragments and cements; the same solutions produced secondary overgrowth on the detrital quartz grains.

(f) Mineralisation of joints and fissures by quartz.—At Coorow Cave vertical joints in the limestones contain normal quartz as joint fillings, and these are contiguous with siliceous laminae (chert) interbedded with the dolomitic limestones of the cave walls. The veins and siliceous laminae are more resistant than the surrounding dolomitic limestones and they stand out on the weathered surface as box-work structures. The presence of these joint fillings at Coorow and elsewhere in the chert not only indicates replacement as a process but also that replacement was a post-lithification feature and did not occur when the sediments were unlithified on the sea floor.

(g) Transgression of bedding by irregular chert masses.—Transgression of bedding by irregular chert masses was advanced as a criterion for replacement by Van Tuyl (1918); such transgression is observed at a number of locations in the Coomberdale Chert.

Clastic Orthoquartzite Members

Clastic members comprise about 40% of the Coomberdale Chert formation and the main features of the three clastic units occurring in the type section are described herein as typical of other clastic members in the formation.

The Noondine Member.—The basal 640 feet of interbedded orthoquartzites and chert in the type section at Coomberdale is a mappable unit termed the Noondine Member.

Sand size clastics predominate in this unit with a grain size range from coarse to very fine in the Wentworth scale of grade; sorting is generally good and the detrital quartz grains are usually well rounded. Secondary enlargement by quartz overgrowth of the quartz grains is very common and in this case the original outlines of the grains are delineated by lines of minute indeterminate inclusions. Most of the orthoquartzites contain chert as a cement (microcrystalline quartz) and there are all lithological variations from pure orthoquartzites to orthoquartzites with chert cements to cherts with detrital quartz to pure cherts.

Current bedding and ripple marking is widespread and testifies to a shallow water environment of deposition. In these conditions a thriving biostromal growth of a tubular colonial organism of unknown affinities (possibly an alga or stromatoporoid) developed in three distinct horizons within the member. All the organic remains are completely silicified. In the uppermost horizon (unit 17 of the type section) the problematica is associated with the stromatolite *Collenia columnaris* Fenton and Fenton in a lithology of very fine-grained orthoquartzite and chert. The stromatolite growth fabric and occurrence gives clear evidence of ecological conditions in the biotope. The algal colonies average 5 mm in cross-section and stand 5 to 20 mm in height. The heads taper towards the base. In general the inter-colony spaces are filled with a fine-grained orthoquartzite in which the detrital quartz grains are approximately 0.12 mm grain size. Two per cent. of the detrital fraction is detrital chert of 0.8 mm average fragment size. There is a high concentration of "heavies," chiefly magnetite and zircon, occurring as a placer deposit in the inter-colony spaces which indicates sediment entrapment under turbulent water conditions. An ecological reconstruction of the environment is given in Table I.

Orthoquartzites with silicified calcareous oolites and cherts with palimpsest oolitic texture throughout the member also indicate deposition in shallow, agitated waters as well as being in themselves first class evidence for the silica replacement of original carbonate rocks which contained them.

The sequence of rock types has an overall shallow neritic to littoral aspect; all the characteristics of these zones as summarised by Kuenen (1950), abundant algae, limestones, oolites and fine to coarse clastics with current-bedding and ripple marks are present.

TABLE I

Ecological Analysis of the Problematic Fossil Biotope—Unit 17

Factors Pertaining to the Substratum

(a) Composition of the substratum:
Fragmental, fine- to medium-grained sand admixed with carbonate mud and particles. Heavy minerals, zircon, magnetite.

(b) Inclination of the substratum:
Unknown.

Factors Operative on the Substratum

(a) Movement of sediment on the substratum:
Individual movement, sorting and concentration of the heavy mineral detrital fraction between algal colonies.

(b) Character and activity of benthonic life:
Dense population of sessile colonial organisms. Tight packing of the problematica tubes. Small stromatolites grow in more open positions.

Factors Pertaining to the Medium

(a) Motion of the medium over the bottom:
Turbulence and directive currents, variable. Excellent size sorting and heavy mineral "placering" in the detrital fraction indicates small range of current velocity with intermittent strong current action and turbulence.

(b) Chemical precipitation:
Periods of calm allow for the organic precipitation of calcium carbonate.

Factors Above the Substratum

(a) Dissolved gas content:
Oxygenation probably normal as evinced by agitation and prolific growth.

(b) Salinity:
Unknown; density of life indicates a large turnover in calcium salts.

(c) Temperature:
Unknown.

(d) Character of the suspensoid load:
Fine sand, mostly quartz, carbonate silt and heavy minerals moved intermittently during times of stronger currents and turbulence. Low turbidity. Larger particles moved in times of strong current action and the finer particles are then in suspension.

(e) Light intensity:
Strong to moderate to meet the photosynthesis requirements of the stromatolite algae.

(f) Depth:
Less than 30 metres.

Kiaka Sandstone Member.—The 380 feet of medium-grained orthoquartzites, cherts and chert breccias termed the Kiaka Member form a mappable unit in the southern outcrop of the formation around Moora. The orthoquartzites are current rippled and thickly bedded; the characteristic lithology of the member is an orthoquartzite with chert fragments. It is a reddish brown, medium-grained, massively bedded rock with 60% detrital quartz grains which are well-rounded and sorted. Approximate average grain diameter is 0.3 mm. Some of the detrital quartz grains are sutured indicating a source in the Archean massif to the east. In character the Kiaka Member is a shallow water deposit of littoral or neritic aspect.

Koolera Sandstone Member.—Lithology of the Koolera Member is dominantly quartz arenites, but a few silty sandstones and siltstone units are interbedded. Clastic chert breccias and conglomerates with orthoquartzite matrix appear at the base of the member. The orthoquartzites range from fine to coarse on the Wentworth scale of grade and the chert fragments from cobble to granule size. As in other clastic members of the formation the detrital quartz grains are often overgrown with quartz in optical continuity with the original grain. Fragments of chert and chert cements are uncommon and often contain minute relict inclusions of calcite.

Bedding is generally massive but asymmetrical current-ripples are present. Irregular mud cracks and mud curls point to desiccation by exposure to the atmosphere at some stages in the depositional history of the member. Limonitic mud balls and clay galls (now often chloritic) of 0.5 to 15 mm diameter are abundant in some of the outcrop.

Sedimentary structures, mud cracks formed by shrinkage of muddy sediments upon exposure of the wet muds to the desiccating influence of the atmosphere and mud curls and mud balls whic originate by penecontemporaneous erosion an deposition of thin lithified muddy layers (mud cracked layers) are indicative of intertidl shallow-water environments. In rolling abo on an agitated sandy bottom the mud bal incorporate sand grains within themselves t form miniature "armoured" mud balls. Curren ripples are also present. Reworking of th deposit has also left its imprint on the wel rounded and well-sorted nature of the detrit quartz fraction.

Clastic Chert Breccias and Conglomerates.—Chert breccias of clastic origin are developed i the Watheroo section of the formation. Thes breccias are distinct lithologically and geneticall from the intraformational chert breccias c slump origin.

The clastic chert breccias are generally inter bedded with orthoquartzites and normally hav a detrital quartz sand matrix and micro crystalline quartz (chert) cement. The brecci fragments range from 0.5 mm to many metre across; the larger fragments are angular bu rounding increases with decreasing size. Th fragments of the stromatolites *Collenia column aris* Fenton and Fenton and *Cryptozoon frequen* Walcott are a particularly striking if rar component of the fragmental fraction. Th quartz matrix is generally medium-grained, well-sorted and the well-rounded nature of the grains is delineated by inclusions despite the overgrowth of authigenic quartz.

The unsilicified equivalent crops out in Jingemia Cave, Watheroo; here, the sandy chert breccias grade down into the unsilicified original rock type—a limestone breccia with sandstone matrix and carbonate cement.

The breccias of the Watheroo sections are true clastic breccias distinct from the breccias of intraformational slump origin. Limestone detritus has been derived from adjacent areas of limestone deposition and lithification such as algal bioherms and biostromes. The presence of broken fragments of the algal stromatolite morphotypes *Collenia columnaris* Fenton and Fenton and *Cryptozoon frequens* Walcott suggests the possibility that these are off-reef talus breccias. The large size of the fragments cannot be reconciled with normal sedimentary transport into lithotopes of sandstone deposition. The extreme variation in size of the fragments in a well-sorted sandy matrix means that this material was selected and deposited indiscriminately and this can be explained by the action of solifluction or turbidity currents; more probably by simple breaking off and movement of the blocks down the steep initial dips on the flanks of the reef structures.

Silicified Carbonate Rocks

In a few rare instances the original dolomitic limestones have escaped the silicification to which the terrain has been subjected. Caves at Coorow and Watheroo are due to solution of these rocks and one outcrop of the original limestone occurs at Moora at the southern extremity of the Coomberdale Chert outcrop. In all cases the limestones are stromatolitic and in them we see the beginnings of silicification.

Ice-borne erratics of the same lithology in the glacial Nangetty Formation (Sakmarian) of the Irwin River Basin have been derived from the Coomberdale Chert. Since these erratics are silicified and here are all stages of replacement from limestone to chert, the plucking of the boulders from their original position and their deposition in the Irwin Basin must post-date silicification, i.e. silicification occurred prior to the Sakmarian and not as Fairbridge (1950) suggests under conditions of deep continental weathering of the Palaeozoic, Mesozoic and part of the Tertiary.

Analyses of the limestones by the volumetric versenate method (Chung *et al.* 1952) to determine CaO/MgO ratio were carried out. SiO_2 and R_2O_3 can be readily estimated within this analytical procedure.

TABLE II

SiO_2, R_2O_3, CaO/MgO Ratio of Dolomitic Limestones from the Coomberdale Chert

Sample No.	SiO_2	R_2O_3	CaO	MgO	CaO/MgO
	%	%	%	%	
36366 (*a*)	6·04	1·15	26·78	19·32	1·38
36366	6·49	0·98	28·92	18·77	1·54
36367	7·60	0·09	27·87	19·44	1·43
36369	8·44	0·06	28·37	19·07	1·48
36368	42·58	0·02	18·89	10·77	1·76
36363	60·48	1·34	11·40	8·46	1·34
34397	66·2	2·00	9·73	6·29	1·54

All the carbonate rocks fall within the dolomitic limestone group of Pettijohn (1956) with high percentages of magnesium carbonate occurring mineralogically as the double carbonate of magnesium and calcium, the mineral dolomite. In the specimens analysed there is a progressive increase of silica from 6 to 66 per cent. and a pure chert is the end member of this silica replacement series.

The typical rock is a gray, crystalline, dolomitic limestone with a stromatolite banding of alternate light and dark gray bands of fine cryptocrystalline calcite (which stain heavily with silver chromate) and bands composed largely of dolomite porphyroblasts. Chert occurs as laminae (2-5 mm), discrete patches and labyrinthic intergrowths transecting the bedding, and it is usually full of small calcite inclusions and occasional "floated" dolomite rhombs. The concentration of dolomite rhombs at the chert-carbonate contact, possibly suggests that silicification was selective on calcite during the early stages of replacement.

Zoned dolomite rhombs contain calcite cores and the core may be selectively attacked so that a rhomboid rim of dolomite surrounds a central area of microcrystalline quartz. The dolomite-calcite zoning is also strong evidence for secondary enrichment in $MgCO_3$ (dolomitisation) which involves recrystallisation of the original limestone with the development of grano-blastic texture. A porphyroblastic texture of dolomite anhedra or euhedra in a matrix of calcite is but a stage towards the completion of the process. Dolomitisation tends to erase existing structures and textures, and if this process goes to completion only faint palimpsest structures are left.

Joint fillings and transgression of the limestone bedding by chert are pertinent to the origin and demonstrate that silicification was a post-lithification feature and not a diagenetic process occurring in the soft sediments at or immediately below the depositional interface. Labyrinthic intergrowth is first class evidence of replacement which cannot be well explained by the other hypotheses of chert origin. The dolomitic limestones at Coorow Cave and Jingemia have a very extensive joint network which has been infilled with vein quartz and chert; beds of chert in the limestone can be traced directly from the joints.

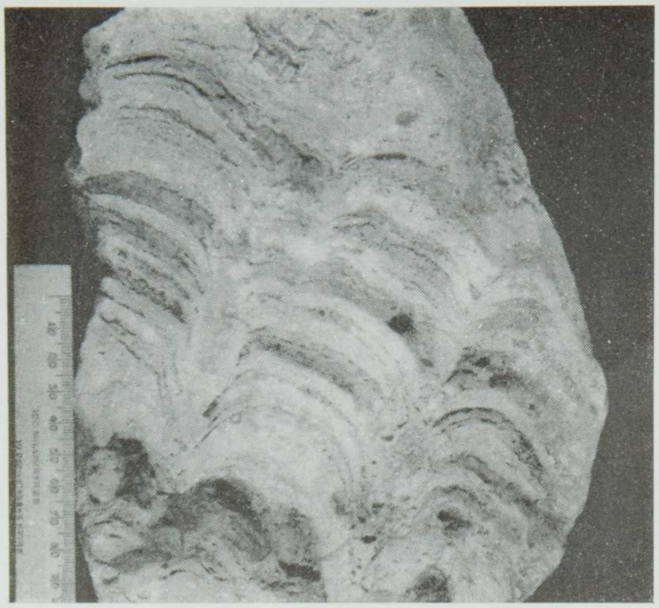
Palaeontology of the Moora Group

The Moora Group is characterised by an abundance of stromatolitic structures many of which are undoubtedly algal in origin. Most of the fossils are located in the Coomberdale Chert and are heavily silicified. Clarke *et al.* (1951) recognised stromatolite rocks in ". . . various stages in the replacement of the original limestone by silica" as erratics in the glacial Nangetty Formation which outcrops in the Irwin River Basin. The realisation that the erratics were derived from the Moora Group (then Yandanooka Group) to the south of the Irwin led to the discovery of algal structures in the Coomberdale Chert at Gunyidi and Moora (Fairbridge 1950). During the work for this paper the present writers have uncovered many more occurrences in the Coomberdale Chert including small biohermal developments.

Stromatolites and stromatolitic sediments are known from rocks of all ages ranging from Precambrian to Recent. Walcott (1914) and Fenton and Fenton (1931, 1933, 1937) have recorded them in biostromal and biohermal developments in the Beltian of North America. In Australia stromatolites have been recorded in the Adelaidean by Mawson and others, and from the Proterozoic rocks of the Northern Territory by Traves (1954). Their occurrence in Recent carbonate sediments in the Bahamas and Florida has been noted by Black (1933), Ginsburg (1955) and Ginsburg and Lowenstam (1958). The form-genera and form-species have little chronological value except perhaps in local correlation (Rezak 1957), but Cloud (1942) and Rezak (1957) have both pointed out the palaeoecological significance of the forms. Rezak in particular has drawn valuable analogies from Recent occurrences in interpreting palaeoecology and palaeogeography in the Beltian.

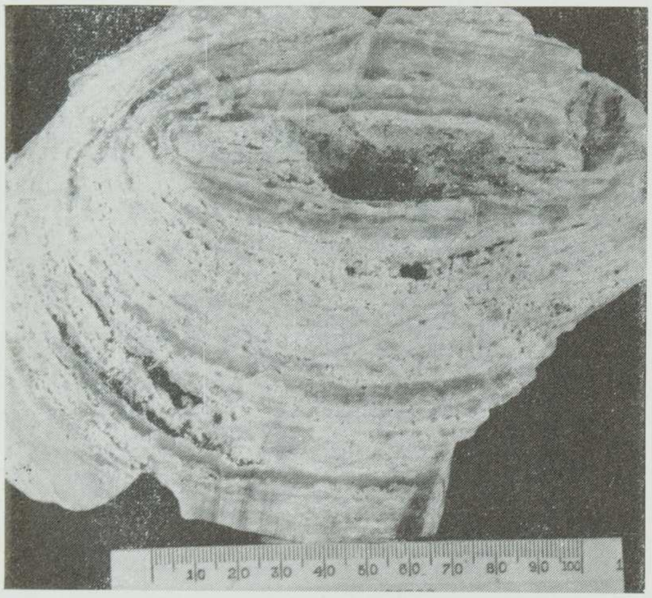
The writers agree with Cloud (1942) that a rigid application of the Binomial Nomenclature to stromatolite forms which are a response to ecological factors rather than specific differences is not strictly valid. However, there seems to be a general agreement among workers that some systematic nomenclature should be applied.

A binomial nomenclature is applied to the stromatolites occurring in the Moora Group, but it is realised that the forms are probably due to the activities of a number of algae and that form is probably a result of interaction of algae with physical factors in the environments. Naming is based only on external form as the only microstructure evident is a crude lamination transverse and upwardly convex.



1

2



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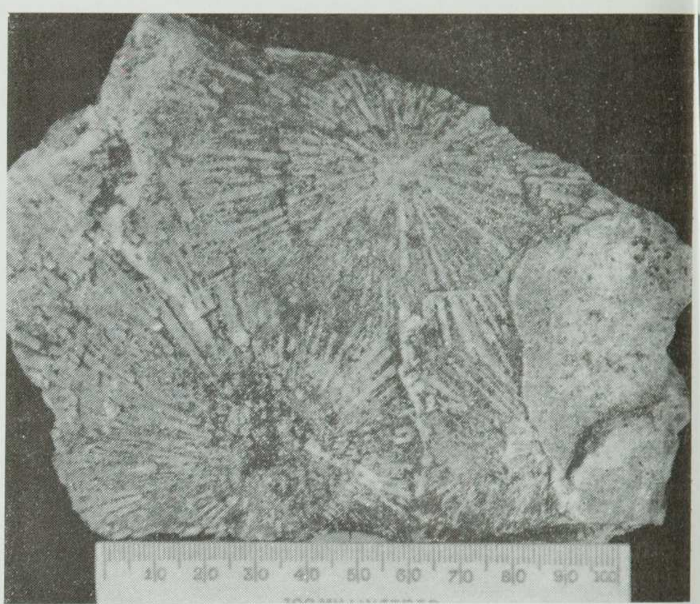

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PLATE II

Fig. 1.—Stromatolite morphotype *Collenia undosa* Walcott in chert from the Coomberdale Chert at Gunyidi, W.A. Note the interruption to the regularity of the laminae at the top of the specimen. Logitudinal section.

Fig. 2.—Stromatolite morphotype *Collenia columnaris* Fenton and Fenton, longitudinal section exposed in a silicified, dolomitic limestone erratic in the Nangetty Formation, Beckett's Gully, Irwin River.

Fig. 3.—Stromatolite morphotype *Cryptozoon frequens* Walcott from a small bioherm in the Coomberdale Chert at Coomberdale. The original limestone has been replaced by chert. Note the flat axial plate in the centre of the colony.

Fig. 4.—Silicified problematica colonies, underside view showing tubes radiating from a central holdfast. Note the orthoquartzite substratum on the right of the specimen. From unit 17 of the Coomberdale Chert type section at Coomberdale.

Collenia undosa Walcott

Plate II, Fig. 1

Walcott, C. D., 1914, *Smithson Misc. Coll.* 64, p. 113, pl. 13, Figs. 1-2; pl. 14, Figs. 1-2.

Fenton, C. L., and Fenton, M. A., 1931, Algae and algal beds in the Belt Series of Glacier National Park. *J. Geol.* 39, p. 684, pl. VI and pl. VII, Figs. 3-5.

Fenton, C. L., and Fenton, M. A., 1937, Belt Series of the north: stratigraphy sedimentation, palaeontology: *Bull. Geol. Soc. Amer.* 48 (4), p. 1947, pl. II, Figs. 3-4, pl. 14, Fig. 3.

Description.—Colonies are compound and united laterally with other colonies. The laminae are irregularly convex upwards and concentric in cross-section. In a few forms the laminae may be regularly convex. But as growth proceeds the laminae pass up into an irregularly convex arrangement. Marginal crowding is a feature of this group of forms and pronounced constriction is seen in longitudinal section. In most specimens silicification has destroyed all but the coarsest lamination.

Specimens occur at Moora, Watheroo, Gunyidi (Fairbridge 1950) in chert; at Coorow Cave in dolomitic limestone and in silicified erratics in the Sakmarian Nangetty Formation. The stromatolites at Coorow Cave are exposed in 20 feet of dolomitic limestone (part silicified) with interbedded orthoquartzites. The limestone is overlain by silty orthoquartzites which have abundant oscillation ripple marks. The stromatolite growth is a biostromal, bedded deposit with a very open lamination.

Collenia columnaris Fenton and Fenton

Plate II, Fig. 2

Fenton, C.L., and Fenton, M. A., 1931, Algae and algal beds in the Belt Series of the Glacier National Park. *J. Geol.* 39, p. 680, pls. 1 and 2.

Fenton, C. L., and Fenton, M. A., 1937, Belt Series of the north: stratigraphy, sedimentation, palaeontology. *Bull. Geol. Soc. Amer.* 48 (4), p. 1941, pl. 9, Figs. 1-2.

Description.—Colonies exhibit a wide range in size; irregularly concentric in cross-section the forms range from 5 mm up to 80 mm in diameter and in longitudinal section from 20 mm to 30 cm (height). The laminae are regularly convex upwards. The long axis of the colonies may be at a steep angle to the bedding. No microstructure is evident save the lamination.

This morphotype occurs in silicified dolomitic limestone erratics in Becketts Gully of the Irwin River area and also occurs with the tubular coral-like problematica in the Noondine Member at Moora.

Cryptozoon frequens Walcott

Plate II, Fig. 3

Walcott, C. D., 1906, *Bull. Geol. Soc. Amer.* 17, pl. II.
Collenia ? frequens Walcott, C. D., 1914, *Smithson. Misc. Coll.* 64, p. 113, pl. 10, Fig. 3.

Collenia frequens Fenton, C. L. and Fenton, M. A., 1931, *J. Geol.* 39, p. 685, pl. 8, Fig. 1.

Description.—Ovoid bodies standing with the long axis at an angle to the bedding; ranging in size from 5 cm to 1 metre in the diameter of the short axis. Crude concentric laminae are grouped around an axial plate or column which is parallel to the long axis of the colony. The outer laminae of colonies may be confluent and some forms appear to have two structureless nuclei. The form occurs in a biohermal growth at Coomberdale and specimens have been collected from a chert breccia at Watheroo.

Fossilum problematicum

Plate II, Fig. 4

Three horizons of the Coomberdale Chert (units 3, 6 and 17 of the type section) contain a tubular colonial organism which has not been identified due mainly to the poor state of preservation of the remains. The problematicum has been submitted to two authorities and different interpretations have been obtained from each. Possible affinities include the tabulate corals, stromatoporoids or algae.

The specimens are completely silicified and consist of numerous closely spaced polygonal tubes with diameters of 2 to 3 mm. The tubes begin at a central holdfast and radiate upwards and outwards as growth proceeds. The outer tubes radiate almost horizontally before assuming a crowded upward growth which simulates some of the tabulate corals in megascopic view. The tube walls are composed of dense fine-grained microcrystalline quartz (chert) with detrital quartz (sand) grains and a few "heavy" minerals incorporated into the mass. The tubes are infilled with coarser-grained microcrystalline quartz with a few patches of normal quartz. The coarser material probably represents post-lithification infilling of former hollow tubes. No intermural structure is evident.

The pre-silicification wall may be pictured as an agglutinate structure with sand grains set in a calcium carbonate base. No corals or stromatoporoids are reported with agglutinate wall structure and the choice lies between two groups, the worms or the algae. The branching behaviour and the presence of a holdfast points to the algal affinities of the organism. The tubes can then be interpreted as lime encrustations around tubular thalli. From the ecological analysis of one problematica biotope (Table I) it is shown that considerable quantities of detritals were in suspension at certain times; the sediment gathering capabilities of the algae are well known and detrital grains impinging onto the thalli would probably be incorporated into the wall structure.

The external similarity of the form to the early tabulate corals has led to the assumption of a lower Palaeozoic age for the Coomberdale Chert (Öpik and Gilbert-Tomlinson 1955). However, if the affinities are algal then the age possibilities range from Precambrian to Recent. At least it can be established that the Moora Group is older than Sakmarian (L. Permian) on stratigraphic grounds. The Moora Group is intruded by dolerite dykes which Prider (1952) believes are probably Upper Proterozoic or Lower Cambrian in age; if this is correct then the age of the Moora Group can only be Precambrian, probably Proterozoic. This dating would also explain the complete lack of organisms other than algae in the Moora sediments which from environmental analysis should contain rich invertebrate faunas if they were deposited later than the Lower Cambrian.

Geological Structure

The Moora Group lies within a fragmented terrain structurally dominated by the Darling Fault. Subsidiary strike faults paralleling and dipping in towards the master rift have a general west-block-down movement similar to the movement on the main fault.

The Darling Fault which forms the present day western edge of the West Australian Precambrian Shield is the major line of crustal weakness of the area, indeed it is one of the larger structural features of the Earth's crust with strong negative gravity anomalies in the west indicating a marginal subsidence in the order of 20,000 to 40,000 feet (Thyer 1951). To the east of the fault the Archean granite and gneiss basement complex unconformably underlies the Moora Group sediments which are only preserved in a narrow 2 to 3 mile wide shatter zone immediately adjacent to the main fracture.

A rapid concentration of gravity anomaly lines (Thyer and Everingham 1956) from the central Perth Basin towards Moora and running thence along the western edge of the Moora Group outcrop via Jingemia to Coorow is an expression of the steep rise of the basement along the fault zone. The proximity of the Darling Fault to Moora is confirmed by the presence of Jurassic continental sediments 615 to 1,195 feet in a deep bore (2,230 feet) situated at approximately 1¼ miles west of the Moora townsite.

The Moora Group sediments form a homoclinal structure within the Darling shatter zone with an average regional dip of 15° W.S.W. to W. There are localised changes in dip direction and magnitude adjacent to faults, the dip in the extreme case may become as much as 50°. The older Archean granites and gneisses underlying the sediments are probably folded on north-north-west to south-south-east trends with variations to north-south. This is in accord with the general north-north-west to south-south-east trend in the Western Australian Precambrian Shield (Prider 1952).

High angle normal or gravity faults are the main structural type in the Moora Group strata; these faults have a north-north-west trend and are sometimes slightly oblique to the strike of the sediments. The fault zones dip steeply (60°-70°) west toward the Darling rift. Movement is west-block-down which results in faulting-off of Moora Group formations and members; stratigraphic throws vary between 400 and 1,500 feet. East-west tensional stress must be regarded as the factor involved in faulting and surface manifestations are accordingly restricted to narrow shear zones, narrow zones of fault breccia, localised drag folding in adjacent sediments and by stratigraphic discrepancy.

A generation of faults with south to south-west trends, oblique to the sediment strike has the effect of breaking the area into a number of fault blocks, while still retaining the homoclinal and 15° W.S.W. to W. regional dip in the sedimentary strata. These faults are probably vertical or dip steeply. The oblique faults could result from a slight transcurrent movement (west-block-south) on the Darling Fault coupled with the main gravity (west-block-down) displacement. The surface manifestations in the dipping strata are the offsetting of sedimentary contacts, drag folding, and dip reversal in the Dalaroo Siltstone. The strike faults are also offset by this oblique faulting, but it is considered that both oblique and strike movements were probably synchronous and represent a post-Moora Group phase in the Darling Fault movements which fractured the eastern and upthrown wall of the Darling Fault into a series of fault blocks.

The movements in the meridional belt adjacent to and east of the Darling Fault between Moora and Coorow are normal faulting and due to east-west tensional stress which may have arisen from either reverse faulting or normal faulting in an underlying and deep-seated master fault (the Darling Fault). No structural evidence exists in the Moora Group strata which indicates the post-Moora Group compressional phase of the Darling earth movements discussed in McWhae *et al.* (1958). The dating of the faulting is very doubtful as palaeontological data regarding the age of the Moora Group are lacking. Quartz dolerite dykes intrude the basal crystalline complex and the Moora Group sediments; there is no displacement of these dykes by either the strike or oblique faults in the Moora Group outcrop so that the fault movements are indicated as pre-dolerite. The dolerite dykes, presumably due to a single taphrogenic episode are regarded as Upper Proterozoic or Lower Cambrian in age by Prider (1952). However, this dating has been questioned by McWhae *et al.* (1958) and until an unequivocal dating of both dolerites and Moora Group is obtained the chronology of the movements must remain a matter of speculation.

Folding in the Moora Group sediments is limited to drag effects adjacent to fault zones. Of the formations the Dalaroo Siltstone is the most susceptible to folding; this phenomenon and bedding plane slippage is a distinct characteristic of the formation. In all cases observed in the field, drag is formed by slippage and indicates the general west-block-down movement in the area.

Conclusion

The geological history of the western edge of the Western Australian Precambrian Shield between Moora and Coorow can be outlined as follows:

1. Formation of the Archean crystalline basement.
2. Deposition of the Capalcarra Sandstone accompanying warping of the craton edge with marine transgression and reworking of the regolith overlying the crystalline basement. Seismic activity and intrusion of sandstone dykes.
3. Deposition of the Dalaroo Siltstone with associated vulcanism and instability.
4. Deposition of the Mokadine Formation with faulting and vulcanism.
5. Deposition of the Coomberdale Chert, limestones, quartz sandstones, oolites; with stromatolite growth, slumping and brecciation. Shallow-water conditions with slow subsidence and slow deposition.

6. Further deposition is not recorded in the Moora Group sequence.

7. Faulting with gravity faulting and fragmentation of the sequence.

8. Silicification and formation of chert.

9. Taphrogeny with dolerite intrusion.

10. Erosion to present day topography.

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